SL IB Chemistry

Your notes

Energy from Fuels

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Combustion Reactions

Combustion Reactions

- **Combustion** is a relatively fast, **thermochemical reaction** that requires:
  - **Fuel**
    - These can include reactive metals, non-metals and organic compounds such as hydrocarbons and alcohols
  - **Oxygen**
    - This reaction with oxygen means that combustion can be categorised as oxidation
    - There are other reactions with oxygen that are oxidation but not combustion, e.g. the rusting of iron
  - A **source of ignition / trigger**
    - This does not automatically mean that a spark or flame is required
    - It can include the build up of heat in a volatile liquid or exposure to high levels of oxygen in certain types of coal, for example
- It is more commonly referred to as burning
- Combustion is accompanied by the generation of heat and light, in the form of flame
  - The heat released from combustion means that the reaction is **exothermic**
- The two types of combustion to consider are:
  - **Complete combustion**
  - **Incomplete combustion**

Combustion of metals

- All metals can **oxidise**, but not all metals can combust
  - Some metals will only combust if they have a **high surface area**, e.g. they are finely divided as filings or a powder

Sparklers demonstrate the combustion of iron

Photo by Jez Timms on Unsplash

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Sparklers are coated with iron powder which gives the characteristic sparks when it undergoes combustion

- Less reactive metals such as copper don't combust
  - Copper does not combust because no flame is formed when it is directly heated in air
  - However, it does oxidise as the surface of the copper metal turns black as copper oxide is formed
- More reactive metals such as those in the s-block will combust in air
  - The s-block metals form **ionic oxides** when they undergo combustion
  - The ionic oxides of these metals are **basic**, i.e. they will react with water to form solutions with a pH > 7
- The standard example of a metal that combusts in air is **magnesium**, which burns with a bright white flame:

magnesium + oxygen → magnesium oxide

$$2Mg\ (s) + O_2\ (g) \rightarrow 2MgO\ (s)$$

- So, the general word equation for the combustion of suitable metals is:

metal + oxygen → metal oxide

Examiner Tip

- **Careful:** When some metals combust, they do not form the typical oxides:
  - Sodium forms sodium peroxide, Na_2O_2
  - Iron forms iron(II, III) oxide, Fe_3O_4
- Since this knowledge is beyond the scope of the specification, you should achieve the marks in an exam for forming the typical oxides, e.g.
  - Sodium oxide, Na_2O
  - Iron(III) oxide, Fe_2O_3

Combustion of non-metals

- Several non-metals show a variety of oxidation states in the different oxides that they form during combustion
- p-block non-metals generally form **covalent oxides** when they undergo combustion
  - These covalent oxides are **acidic**, i.e. they will react with water to form solutions with a pH < 7
- A common example of a non-metal that combusts in air is **sulfur**, which burns with a blue flame

sulfur + oxygen → sulfur dioxide

$$S\ (s) + O_2\ (g) \rightarrow SO_2\ (g)$$

- So, the general word equation for the combustion of non-metals is:

non-metal + oxygen → non-metal oxide

Your notes

Worked example

Combustion of metals and non-metals

1. Potassium produces a lilac flame when it burns in air to form potassium oxide, K_2O. Write a chemical equation for this reaction.
2. Write a chemical equation for the combustion of white phosphorous, P_4, to form phosphorous(V) oxide, P_4O_{10}.

Answer 1:

- The chemical symbol for potassium is K
- The chemical formula for oxygen is O_2
- The chemical formula of potassium oxide is given as K_2O
- So, the unbalanced chemical equation is:
  - $K + O_2 \rightarrow K_2O$
- Doubling the K_2O balances the oxygen atoms
- Consequently, four potassium atoms are required on the reactant side to balance the equation
- The balanced chemical equation is:
  - $\mathbf{4K + O_2 \rightarrow 2K_2O}$

Answer 2:

- The chemical formula for white phosphorous is given as P_4
- The chemical formula for oxygen is O_2
- The chemical formula of phosphorus(V) oxide is given as P_4O_{10}
- So, the unbalanced chemical equation is:
  - $P_4 + O_2 \rightarrow P_4O_{10}$
- The phosphorous atoms are balanced on both sides of the equation
- There are 10 atoms of oxygen on the products side of the equation, which means that $5O_2$ are required on the reactant side to balance the equation
- The balanced chemical equation is:
  - $\mathbf{P_4 + 5O_2 \rightarrow P_4O_{10}}$

Complete combustion of organic compounds

- Many organic compounds are used as fuels because they release relatively large amounts of energy when combusted
- They do not usually undergo spontaneous combustion because their combustion reactions have a high activation energy
  - This makes fuels easy and safe to transport and store
  - For more information about activation energy, see our revision note on activation energy
- The organic compounds that are commonly used as fuels include:
  - Hydrocarbons - particularly alkanes
  - Alcohols

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What is complete combustion?

- When fuels such as hydrocarbons and alcohols are burnt in **excess** (plenty of) oxygen, **complete combustion** takes place
  - This means that all carbon and hydrogen will be oxidised
  - Therefore, the products of complete combustion are **carbon dioxide** and **water**
- The word equation for **complete combustion** is:

fuel + oxygen → carbon dioxide + water

Combustion of hydrocarbons

- For example, the word and chemical equations for the complete combustion of methane are:
  - Complete combustion of methane word equation:

methane + oxygen → carbon dioxide + water

  - Complete combustion of methane chemical equation:

$$CH_4\,(g) + 2O_2\,(g) \rightarrow CO_2\,(g) + 2H_2O\,(l)$$

Combustion of Alcohols

- Alcohols react with oxygen in the air when ignited and undergo **complete combustion** to form carbon dioxide and water

alcohol + oxygen → carbon dioxide + water

- For example, the word and chemical equations for the complete combustion of ethanol are:
  - Complete combustion of ethanol word equation:

ethanol + oxygen → carbon dioxide + water

  - Complete combustion of ethanol chemical equation:

$$C_2H_5OH\,(l) + 3O_2\,(g) \rightarrow 2CO_2\,(g) + 3H_2O\,(l)$$

Examiner Tip

Be careful when balancing equations for the combustion of alcohol, as students often forget to count the oxygen in the alcohol

- Lower alcohols burn with an almost invisible flame and make good fuels
- **Ethanol** can be produced sustainably as a fuel by the **fermentation** of sugars
- However, the **energy density** (the amount of energy in kJ per kg of fuel) is lower than gasoline so cars that run on ethanol must either have a larger fuel tank or fill up more often
- Blending **ethanol** with gasoline or diesel increases the **energy density** and makes it safer in case of fires as it is easier to see the flames compared to pure **ethanol** burning
- However, there are socio-economic concerns about using large quantities of farmland to produce crops for fermentation, which could be better used for food production

Your notes

Worked example

Complete combustion of hydrocarbons and alcohols

Write chemical equations for the complete combustion of:

1. Propane, C_3H_8
2. Propan-1-ol, C_3H_7OH

Answer 1:

- Since this is complete combustion, the products will be carbon dioxide and water
- So, the unbalanced chemical equation is:
  - $C_3H_8 + O_2 \rightarrow CO_2 + H_2O$
- The 3 carbons in propane will form $3CO_2$
- The 8 hydrogens in propane will form $4H_2O$
- This updates the unbalanced chemical equation to:
  - $C_3H_8 + O_2 \rightarrow 3CO_2 + 4H_2O$
- There are now 10 oxygens in total on the product's side, which means that $5O_2$ are required on the reactant side to balance the equation
- The balanced chemical equation is:
  - $\mathbf{C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O}$

Answer 2:

- Since this is complete combustion, the products will be carbon dioxide and water
- So, the unbalanced chemical equation is:
  - $C_3H_7OH + O_2 \rightarrow CO_2 + H_2O$
- The 3 carbons in propan-1-ol will form $3CO_2$
- The 8 hydrogens in propan-1-ol will form $4H_2O$
- This updates the unbalanced chemical equation to:
  - $C_3H_7OH + O_2 \rightarrow 3CO_2 + 4H_2O$
- There are now 10 oxygens in total on the product's side **AND** one oxygen on the reactants side
  - This means that $4\frac{1}{2}O_2$ are required on the reactant side to balance the equation
- The balanced chemical equation is:
  - $\mathbf{C_3H_7OH + 4\frac{1}{2}O_2 \rightarrow 3CO_2 + 4H_2O}$
    OR
    $\mathbf{2C_3H_7OH + 9O_2 \rightarrow 6CO_2 + 8H_2O}$, giving whole number coefficients

Your notes

Incomplete Combustion

Incomplete Combustion

- Complete combustion occurs with a plentiful supply of air / oxygen and produces carbon dioxide and water
  - In a Bunsen burner, complete combustion is characterised by a blue, non-luminous flame
- In comparison, incomplete combustion:
  - Has a limited supply of air / oxygen
  - Still produces water
    - This is the combustion / oxidation product of the hydrogen present in organic compounds
  - Produces carbon monoxide or carbon
    - These are the combustion / oxidation products of the carbon present in organic compounds as it is not fully oxidised
- Incomplete combustion often takes place inside a **car engine** and inside **faulty boilers** due to the limited amount of oxygen present
- In a Bunsen burner, incomplete combustion is characterised by a yellow flame

Carbon monoxide as a product of incomplete combustion

- With a reduced supply of oxygen, carbon monoxide will be produced
- The word equation for **incomplete combustion** to form carbon monoxide is:

Fuel + oxygen → carbon monoxide + water

- For example, the word and chemical equations for the incomplete combustion of propane to form carbon monoxide are:
  - Incomplete combustion of propane word equation:

    Propane + oxygen → carbon monoxide + water

  - Incomplete combustion of propane chemical equation:

    C_3H_8 (l) + 3½O_2 (g) → 3CO (g) + 4H_2O (l)

- Carbon monoxide is extremely dangerous as it is **colourless** and **odourless** (it doesn't smell) and will not be noticed
- Carbon monoxide is also a **toxic** and **poisonous** gas that binds irreversibly to haemoglobin in the blood
  - This limits the haemoglobin's capacity to bind and transport **oxygen**
- As no oxygen can be transported around the body, victims will feel **dizzy, lose consciousness** and if not removed from the carbon monoxide, they can **die**

Carbon as a product of incomplete combustion

- With a very reduced supply of oxygen, carbon will be produced in the form of soot
  - A sooty, yellow flame is a clear indication that incomplete combustion is taking place
  - Many hydrocarbons derived from benzene burn with a sooty, yellow flame due to their high percentage of carbon content
- The production of soot can be used to distinguish between different organic compounds

Your notes

- Compounds with a higher percentage of carbon content tend to undergo incomplete combustion and produce more soot

Worked example

Incomplete combustion as a qualitative measure

1. Calculate the percentage carbon composition by mass in samples of cyclohexane (C_6H_{12}), nitrobenzene ($C_6H_5NO_2$) and naphthalene ($C_{10}H_8$).

	cyclohexane (C_6H_{12})	**nitrobenzene ($C_6H_5NO_2$)**	**naphthalene ($C_{10}H_8$)**
M / g mol^{-1}	84	123	128
% of carbon			

2. Using your answer to part (1), explain how the three samples could be distinguished by observing their combustion.

Answer 1:

- The percentage carbon composition by mass is calculated by:

$$\frac{\text{total mass of carbon}}{M_r} \times 100$$

	cyclohexane (C_6H_{12})	**nitrobenzene ($C_6H_5NO_2$)**	**naphthalene ($C_{10}H_8$)**
M / g mol^{-1}	84	123	128
% of carbon	**86**	**59**	**94**

Answer 2:

- Napthalene will produce the most sooty flame
- Nitrobenzene will produce the least sooty flame

- The word equation for **incomplete combustion** to form carbon is:

fuel + oxygen → carbon + water

- For example, the word and chemical equations for the incomplete combustion of propane to form carbon are:
  - Incomplete combustion of propane word equation:

propane + oxygen → carbon + water

- Incomplete combustion of propane chemical equation:

$$C_3H_8\ (l) + 2O_2\ (g) \rightarrow 3C\ (s) + 4H_2O\ (l)$$

Examiner Tip

- The incomplete combustion of organic compounds never produces hydrogen
- Hydrogen is always preferentially oxidised by any available oxygen, rather than carbon

Your notes

The Amount of Carbon Dioxide Produced When Fuels Burn

Your notes

The Amount of Carbon Dioxide Produced When Fuels Burn

Fossil fuels

What is a fossil fuel?

- A **fossil fuel** is a material such as **coal**, **oil** and **natural gas**
- Fossil fuels contain **hydrocarbons**
- They were formed naturally in the Earth's crust from the remains of **dead plants and animals** millions of years ago
- They are described as **non-renewable** or **finite** because they cannot be replaced in a short period of time

Advantages of fossil fuels

Coal

- Relatively cheap
- Abundant
- Long lifespan (compared to other fossil fuels)
- Can be converted into liquid fuels and gases
- Relatively safe
- Products from the combustion of coal have other uses, e.g. ash can be used to make roads

Oil

- Easy to store and transport in pipelines and tankers
- Impurities can be easily removed
- Releases a lot of energy per kg
  - Known as high energy / enthalpy density
- Easily processed
  - Fractional distillation and cracking are used to produce other useful chemicals, e.g. shorter-chain alkanes and alkenes

Natural gas

- Cheapest of the fossil fuels
- Easy to store and transport in pipelines and pressurised containers
- Large amounts of energy per unit mass
  - Known as high specific energy
- Relatively clean
  - Complete combustion of natural gas happens with a blue flame producing minimal to no harmful compounds
  - Does not contribute to acid rain

Disadvantages of fossil fuels

- All fossil fuels have limited lifespans / supplies, i.e are finite

Coal

- Combustion produces large amounts of pollution
  - Carbon dioxide
  - Sulfur dioxide
  - Particulates
- Associated with:
  - Global warming
  - Acid rain
  - Global dimming / visual pollution
- Difficult to transport
- Issues around mining:
  - Destruction of habitats
  - Noise pollution
  - Health of miners
  - Safety issues
- Potentially radioactive

Oil

- Combustion produces large amounts of pollution, including:
  - Carbon dioxide
  - Sulfur dioxide
  - Carbon monoxide
- Associated with:
  - Global warming
  - Acid rain
  - Global dimming / visual pollution
  - Photochemical smog
- Uneven worldwide distribution
- Oil spills affecting habitats
- Safety issues around drilling

Natural gas

- Combustion produces large amounts of pollution
  - Carbon dioxide
- Associated with:
  - Global warming
- Expensive and time-intensive to produce
- Expensive to store
- Safety issues around storage in pressurised containers

Burning fuels

- Many different fuels are used in everyday life
  - The choice of fuel used can depend on:

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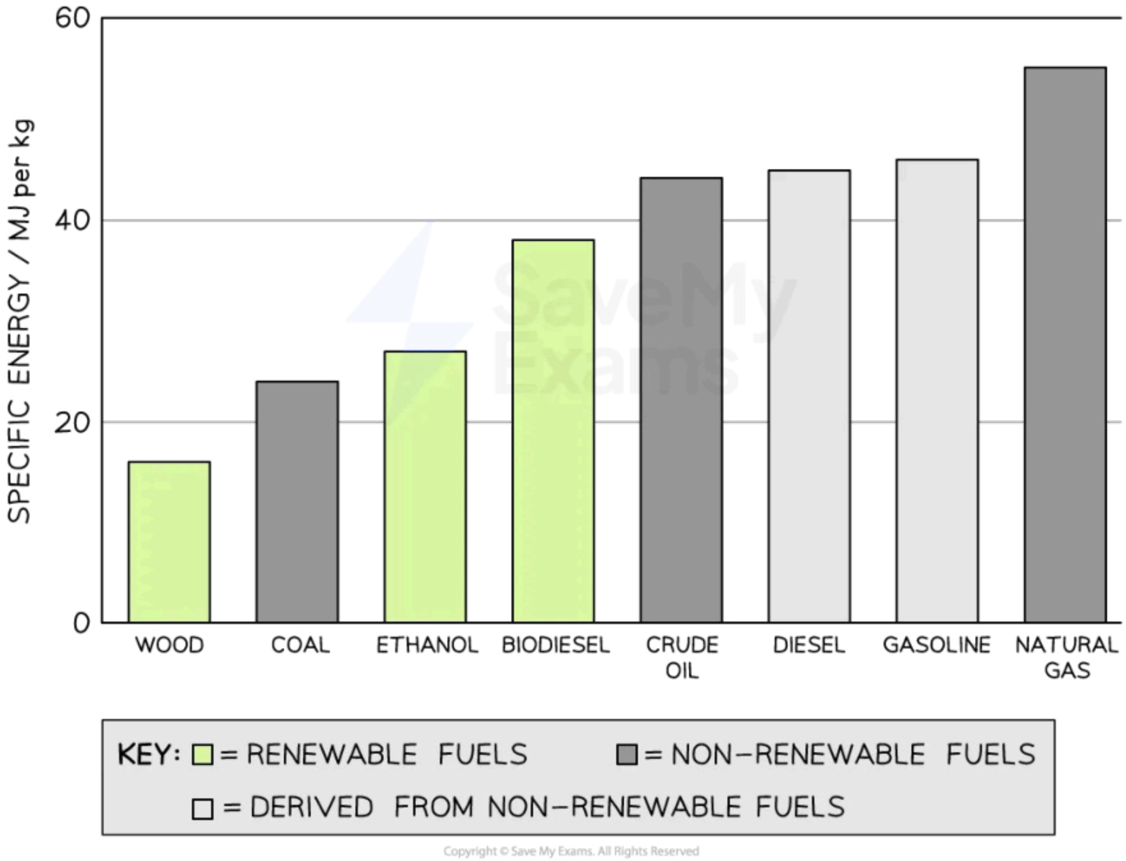
- Availability of the fuel
- Cost
- Intended use
- Energy requirements
- All fuels can undergo combustion to release the chemical energy stored within their bonds
  - Specific energy is a measure of the energy stored in a substance

The specific energy of different common fuels



Different fuels release different amounts of energy when combusted

- It is the hydrocarbon contained within the fossil fuel (and other fuels) that undergoes combustion
- **Remember:** Complete combustion of hydrocarbons results in the production of carbon dioxide and water, while incomplete combustion results in the production of carbon monoxide / carbon and water
  - Both types of combustion are exothermic, so they release energy
- As the length of the hydrocarbon chain increases
  - There is an **increased carbon content** resulting in the production of more carbon dioxide and carbon monoxide / carbon
  - There are stronger **London dispersion forces**, which makes the hydrocarbon **less volatile**
  - The hydrocarbon **releases less energy** per unit mass of fuel

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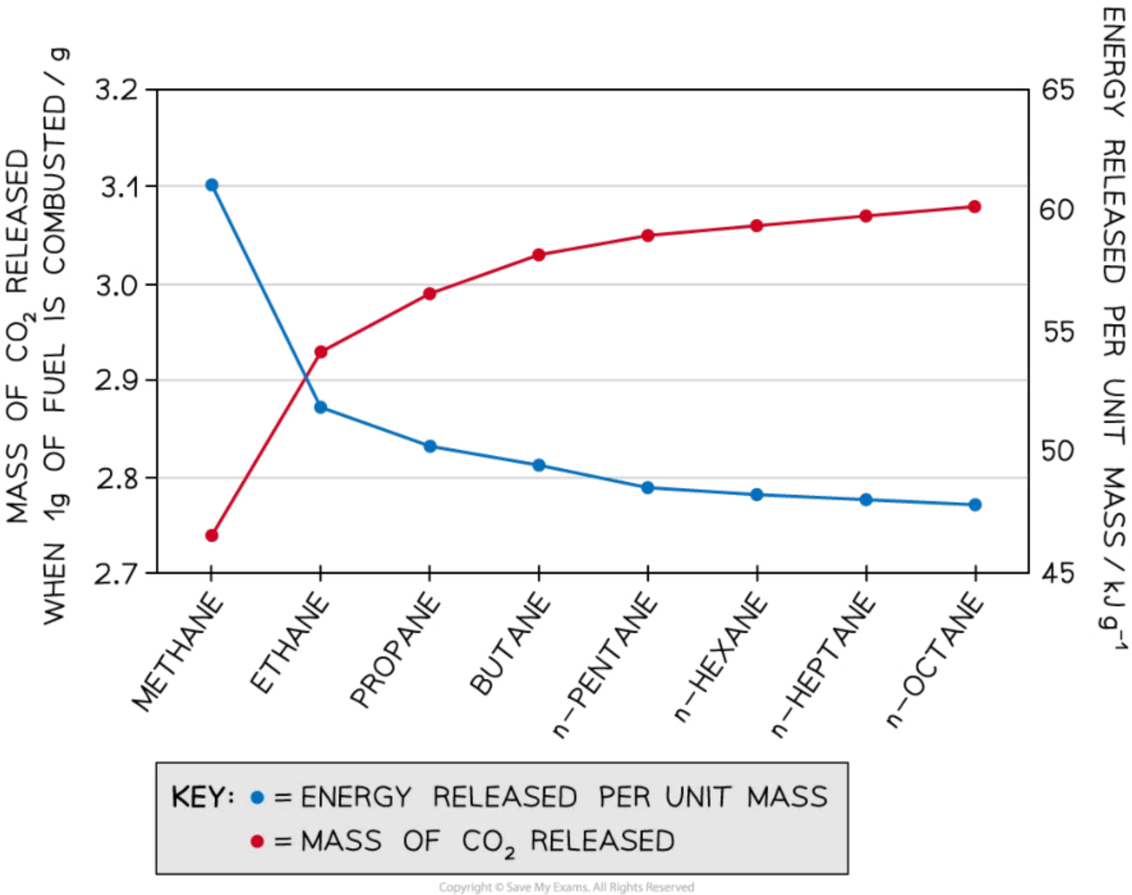
Graph showing the mass of carbon dioxide and amount of energy released during the combustion of the first eight straight-chain alkanes



As the length of the hydrocarbon chain increases, more carbon dioxide and less energy is released per gram of hydrocarbon burnt

- As the length of the hydrocarbon increases, it is also more likely that incomplete combustion will take place

Examiner Tip

- Students often miss that methane releases the most energy per unit mass of fuel

Your notes

Worked example

Calculate the mass of carbon dioxide produced when 1.00 g of butane undergoes complete combustion.

Answer:

- Start with the balanced chemical equation:
  - C_4H_{10} (g) + 6½O_2 (g) → 4CO_2 (g) + 5H_2O (l)
- Calculate the moles of butane, using moles = $\frac{\text{mass}}{M_r}$:
  - n (C_4H_{10} (g)) = $\frac{1.00}{((4 \times 12.01) + (10 \times 1.01))}$
  - n (C_4H_{10} (g)) = 0.0172 moles
- Use the stoichiometry of the balanced chemical equation to deduce the moles of carbon dioxide produced:
  - 1 C_4H_{10} : 4 CO_2
  - n (CO_2 (g)) = 4 x n (C_4H_{10} (g))
  - n (CO_2 (g)) = 4 x 0.0172
  - n (CO_2 (g)) = 0.0688 moles
- Calculate the mass of carbon dioxide produced, using mass = moles x M_r
  - Mass of CO_2 = 0.0688 x (12.01 + (2 x 16.00)
  - **Mass of CO_2 produced when 1.00 g of butane undergoes complete combustion = 3.03 g**

Carbon Dioxide Levels & the Greenhouse Effect

Your notes

Carbon Dioxide Levels & the Greenhouse Effect

Carbon dioxide levels

- The amount of **carbon dioxide** (and carbon) in the atmosphere is increasing, mainly due to human activities such as:
  - Combustion, including
    - Electricity generation - estimated at around 85% of all fossil fuel consumption
    - Transportation
  - Construction
  - Deforestation / conversion of land from forestry to farming
  - Increased livestock farming
    - Livestock, such as cattle, release **methane** into the atmosphere
- Both carbon dioxide and methane gases contribute to atmospheric carbon levels and influence global temperatures
- The main reason for increasing carbon dioxide levels is the combustion of fossil fuels which releases carbon that has been stored for millions of years
  - **Increased use of fossil fuels** is contributing to an increase in the carbon dioxide content of the atmosphere

- Scientists from research stations, such as the Mauna Loa Observatory, have been taking **quantitative measurements** of atmospheric carbon dioxide (and methane) concentrations for many years
  - Scientists have records for carbon dioxide levels dating back to 1958 and for methane levels from 1984

Graph of carbon dioxide levels over time

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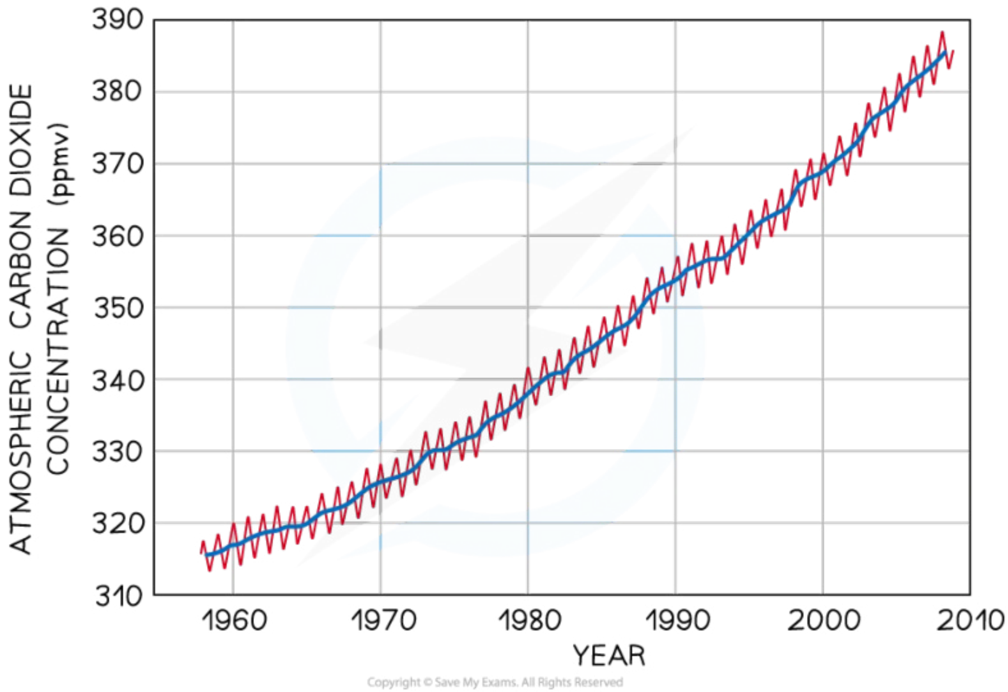

There has been a general increase in the volume of carbon dioxide over the years (blue line) with annual fluctuations (red line) due to seasonal changes in photosynthesis rates

- The amount of carbon dioxide is constantly changing due to seasonal fluctuations in rates of photosynthesis
  - Photosynthesis removes carbon dioxide from the atmosphere

What are greenhouse gases?

- A greenhouse gas is a gas that absorbs radiation emitted from the Earth's surface, trapping it in the atmosphere so that it is not lost to space
  - Greenhouse gases in the atmosphere have a similar effect to the glass in a greenhouse, hence the term greenhouse gas and their effect is known as the **greenhouse effect**
- The greenhouse effect is important to ensure that Earth is warm enough for life
  - Without the insulating effects of greenhouse gases, Earth would see similar temperature fluctuations to planets such as Mars, where temperatures range from 20°C to –153°C
- There are many greenhouse gases, including:
  - **Carbon dioxide** - produced when living organisms respire and when fuels are burned
  - **Methane** - produced by livestock and landfill sites as well as being released during mining
  - **Nitrous oxides** - commonly released during the combustion of impurities in fossil fuels
  - **Water vapour** - produced during combustion as well as by evaporation of the oceans and lakes as part of the water cycle
- The major focus of greenhouse gases and the greenhouse effect is the action of **atmospheric carbon dioxide**
  - Sources of atmospheric carbon dioxide include:

- Combustion of wood and fossil fuels
- Respiration of plants and animals
- Thermal decomposition of carbonate rocks
- The effect of acids on carbonates

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What is the greenhouse effect?

- When shortwave radiation from the sun strikes the Earth's surface it is absorbed and **re-emitted** from the surface of the Earth as infrared radiation
- The infrared radiation passes through the atmosphere where some thermal energy passes straight through and is emitted into space
- But some infrared radiation is absorbed by greenhouse gases and re-emitted in all directions
- This reduces the thermal energy lost into space and traps it within the Earth's atmosphere, keeping the Earth warm
- This process is known as the **greenhouse effect**
- As the concentration of greenhouse gases in the atmosphere increases due to human activity, more thermal energy is trapped within the Earth's atmosphere causing the Earth's average temperature to rise (global warming)
- This process is called the **enhanced greenhouse effect**

Greenhouse effect diagram

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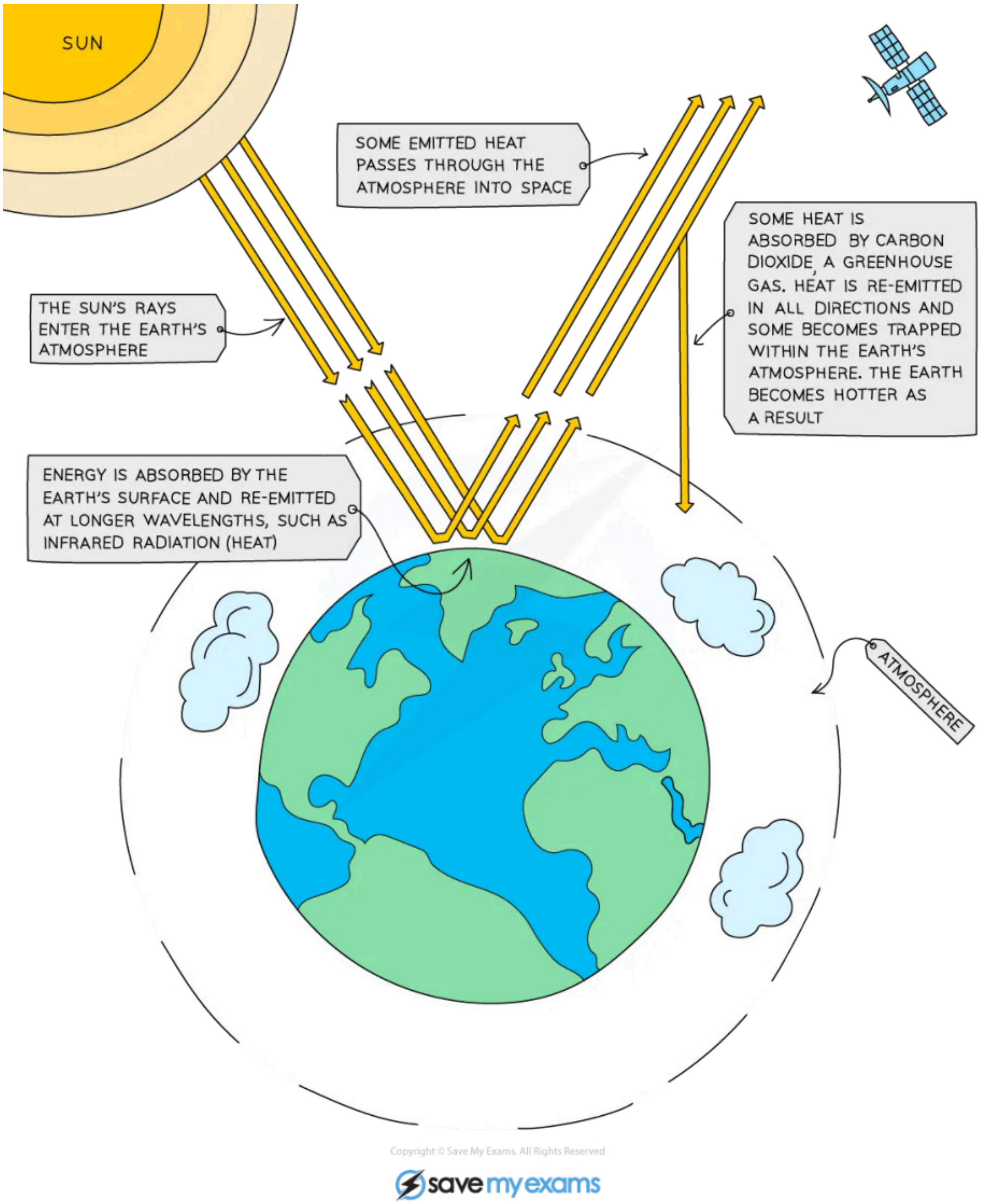

Greenhouse gases absorb the infrared radiation emitted by Earth, warming the atmosphere

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Biofuels

Biofuels

What is the difference between renewable and non-renewable resources?

Renewable resources

- **Renewable resources** will not run out in the foreseeable future because they can be replaced over a relatively short period of time
- They can also be called infinite
- They can be considered **sustainable** as they can be produced at the same rate, or faster, than they are being used
- **Biofuels** are an example of a renewable resource

Non-renewable resources

- **Non-renewable resources** will run out in the foreseeable future as there are limited supplies
  - They cannot be replaced within a short time period
- They can also be called finite
- They are not a **sustainable** resource
- Fossil fuels are an example of a non-renewable resource

Reasons for the development of biofuels and other renewable resources:

- Reduce pollution from the combustion of fossil fuels
- Have positive impacts on global warming and **climate change**
- The finite supply / limited amount and depletion of fossil fuels, which are non-renewable resources

What is a biofuel?

- The three main biofuels are:
  - Bioethanol
  - Biodiesel
  - Biogas
- Biofuels are made from organic compounds
- These organic compounds are produced by **biological carbon fixation**

Bioethanol

- Green plants absorb **atmospheric carbon dioxide** and convert it into **glucose** via **photosynthesis**
  - Word equation for photosynthesis:

$$\text{carbon dioxide} + \text{water} \rightarrow \text{glucose} + \text{oxygen}$$

  - Symbol equation for photosynthesis:

$$6CO_2\,(g) + 6H_2O\,(l) \rightarrow C_6H_{12}O_6\,(aq) + 6O_2\,(g)$$

- The glucose is then further converted into **ethanol** by **fermentation**
  - The name bioethanol is simply identifying how the ethanol has been produced

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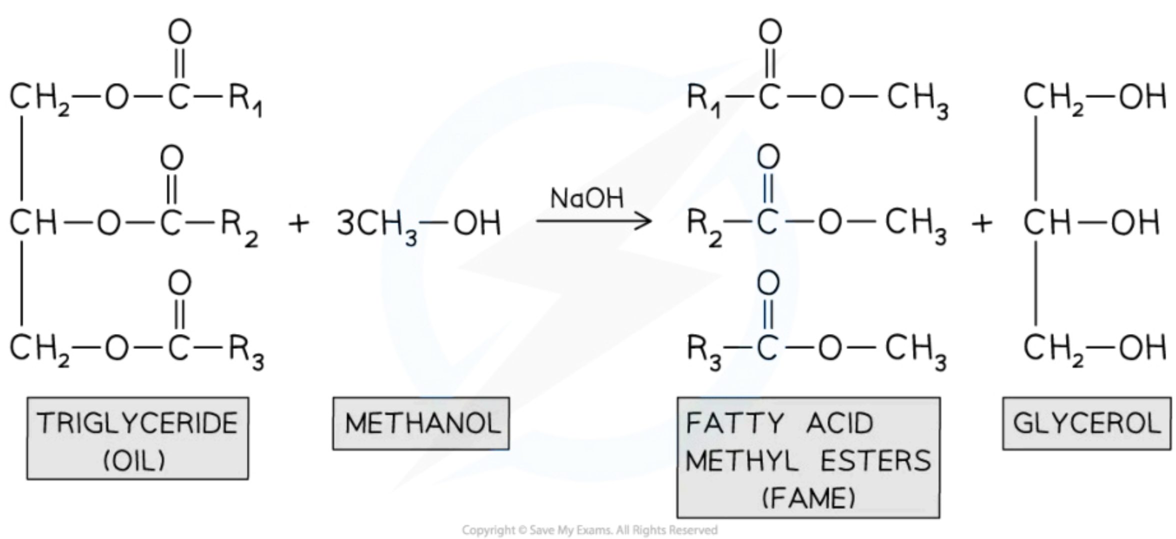
- When biofuels are produced this way, they can be considered **carbon neutral**
  - This is because the carbon dioxide absorbed during photosynthesis equals the carbon dioxide produced by the combustion of the biofuel

Biodiesel

- Biodiesel is made from renewable vegetable oils rather than non-sustainable petrochemicals
- Natural triglyceride oils are converted to esters of methanol, which makes them less viscous
- Biodiesel made from rapeseed oil, for example, is produced by **transesterification**
  - The triglyceride is converted into the less viscous fatty acid methyl ester (FAME) using methanol
    - An acid works by protonating the carbonyl group
    - An alkali works by deprotonating the alcohol / methanol
    - However, it is more common to use an alkaline catalyst such as NaOH / KOHAcids and alkalis can both be used to catalyse the reaction
- The transesterification is reversible, so an excess of methanol is used to drive the equilibrium to the right
- Under optimum conditions, this process can produce a very successful yield of 98%

How to make biodiesel



Transesterification forming methyl esters

Biogas

- Biogas is a renewable fuel that is released when organic matter, such as food or animal waste, is broken down by microorganisms in the absence of oxygen
- It consists mainly of methane and carbon dioxide but can also include small amounts of hydrogen sulphide and other chemicals
- The relative amounts of the components of biogas depend on the type of waste used
  - The bacterial decomposition of carbohydrates such as produces biogas with 50.0% methane content

$$C_6H_{12}O_6\,(s) \rightarrow 3CO_2\,(g) + 3CH_4\,(g)$$

- Fatty acids such as heptadecanoic acid, commonly called oleic acid, can undergo bacterial decomposition in a more moisture-rich environment to produce biogas with a 69.4% methane content

$$4C_{17}H_{33}COOH\,(l) + 34H_2O\,(l) \rightarrow 21CO_2\,(g) + 51CH_4\,(g)$$

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Advantages of biofuel

- Carbon neutral, renewable and sustainable if crops / trees are replanted
- Reduce greenhouse emissions / pollution
- Biodiesel and biogas can reduce the amount of waste going to landfill sites as the waste can be used to produce them
- Biofuel production could provide money for less developed countries as they have the space to grow the crops required
- Can provide jobs in the agriculture and energy sectors

Disadvantages of biofuel

- High costs
  - Conversion of engines and machinery to run on biofuels instead of petrol / diesel
  - Harvesting and transportation
- Many developed countries don't have the space to be able to produce enough plants to make biofuels because the land is needed for food production
  - This can lead to deforestation in an effort to meet the demand
- Removes nutrients from the ground / uses large amounts of fertilisers and pesticides
- Biofuels typically have lower specific energy than fossil fuels

Your notes

Fuel Cells

Fuel Cells

What are fuel cells?

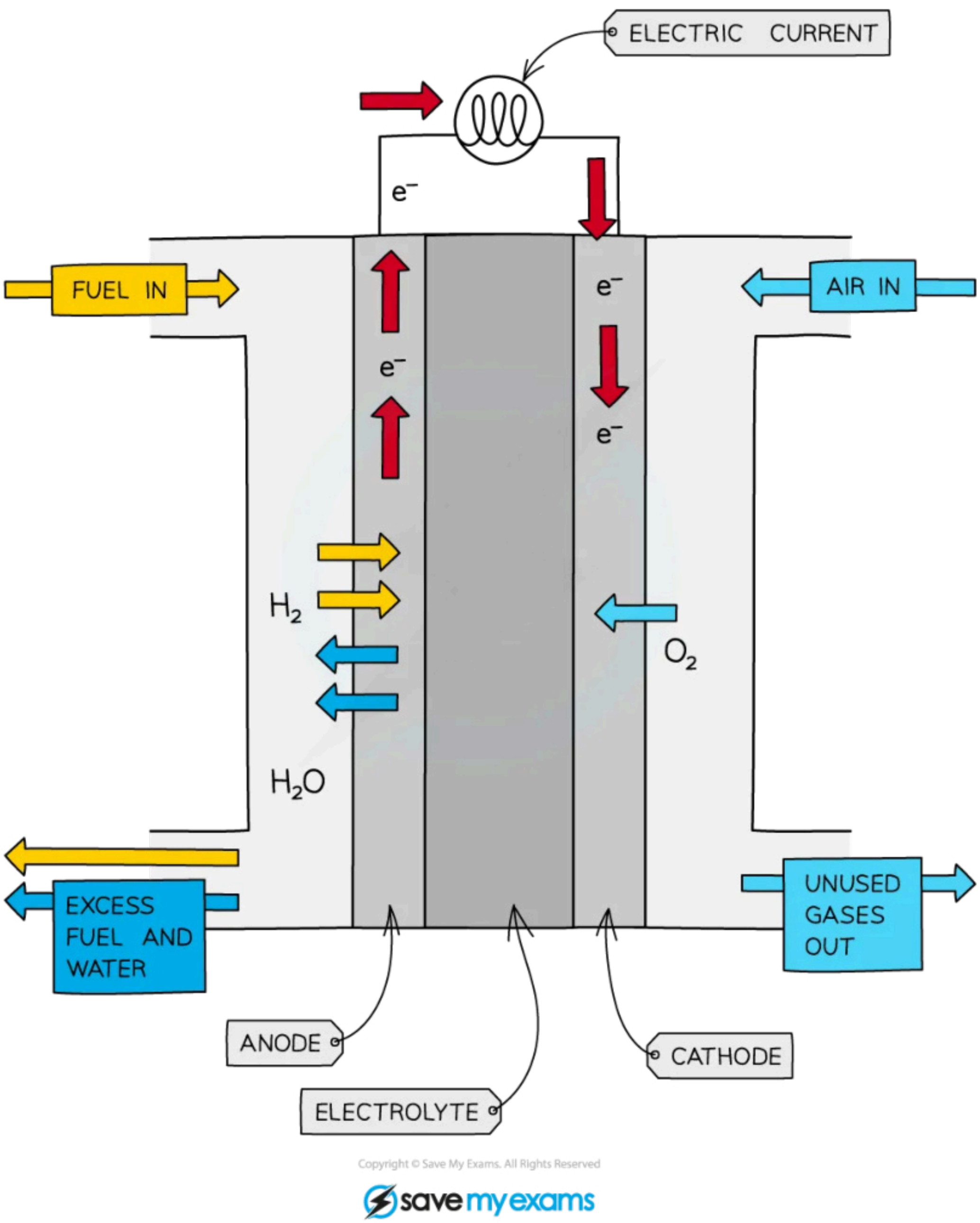
- A fuel cell is an electrochemical cell in which a fuel **donates** electrons at one electrode and oxygen **gains** electrons at the other electrode
- These cells are becoming more common in the automotive industry to replace petrol or diesel engines

How do fuel cells work?

- As the fuel enters the cell it becomes oxidised which sets up a **potential difference** or voltage within the cell
- Different electrolytes and fuels can be used to set up different types of fuel cells
- An important cell is the **hydrogen-oxygen** fuel cell

The hydrogen-oxygen fuel cell

Your notes



The hydrogen-oxygen fuel cell combines both elements to release energy and water

- The fuel cell consists of
  - a reaction chamber with separate inlets for hydrogen and oxygen gas
  - an outlet for the product - water
  - an electrolyte of aqueous sodium hydroxide

- a semi-permeable membrane that separates the hydrogen and oxygen gases
- The half equations are:

$$2H_2\,(g) + 4OH^-\,(aq) \rightarrow 4H_2O\,(l) + 4e^- \qquad E^\theta = -0.83\,V$$

$$O_2\,(g) + 2H_2O + 4e^- \rightarrow 4OH^-\,(aq) \qquad E^\theta = +0.40\,V$$

- The overall reaction is found by combining the two half equations and cancelling the common terms:

$$2H_2\,(g) + 4OH^-\,(aq) + O_2\,(g) + 2H_2O + 4e^- \rightarrow 4H_2O\,(l) + 4e^- + 4OH^-\,(aq)$$

$$2H_2\,(g) + O_2\,(g) \rightarrow 2H_2O\,(l) \qquad E^\theta = +1.23\,V$$

Advantages of hydrogen fuel cells

- Water is the only reaction product, so fuel cells present obvious environmental advantages over other types of cells
- The reaction is the same as hydrogen combusting in oxygen, but since the reaction takes place at room temperature without combustion, all the bond energy is converted into electrical energy instead of heat and light
- There are no harmful oxides of nitrogen produced, which are usually formed in high-temperature combustion reactions where air is present
- Fuel cells have been used on spacecraft, where the product can be used as drinking water for astronauts

Disadvantages of hydrogen fuel cells

- Hydrogen is a highly flammable gas and the production and storage of hydrogen carries safety hazards
- Very thick walled cylinders and pipes are needed to store hydrogen which has economic impacts
- The production of hydrogen is a by-product of the crude oil industry, which means it relies on a non-renewable, finite resource
- Until a cheap way is found to make hydrogen, its widespread use in fuel cells will be limited
- Hydrogen has high energy density, that is, the amount of energy contained in 1g of the fuel is high compared to other fuels, but because it is a gas, its energy density per unit volume is low which means larger containers are needed compared to liquid fuels

Examiner Tip

One difference between fuel cells and other cells is that the cell operates continuously as long as there is a supply of hydrogen and oxygen; the energy is not stored in the cell.

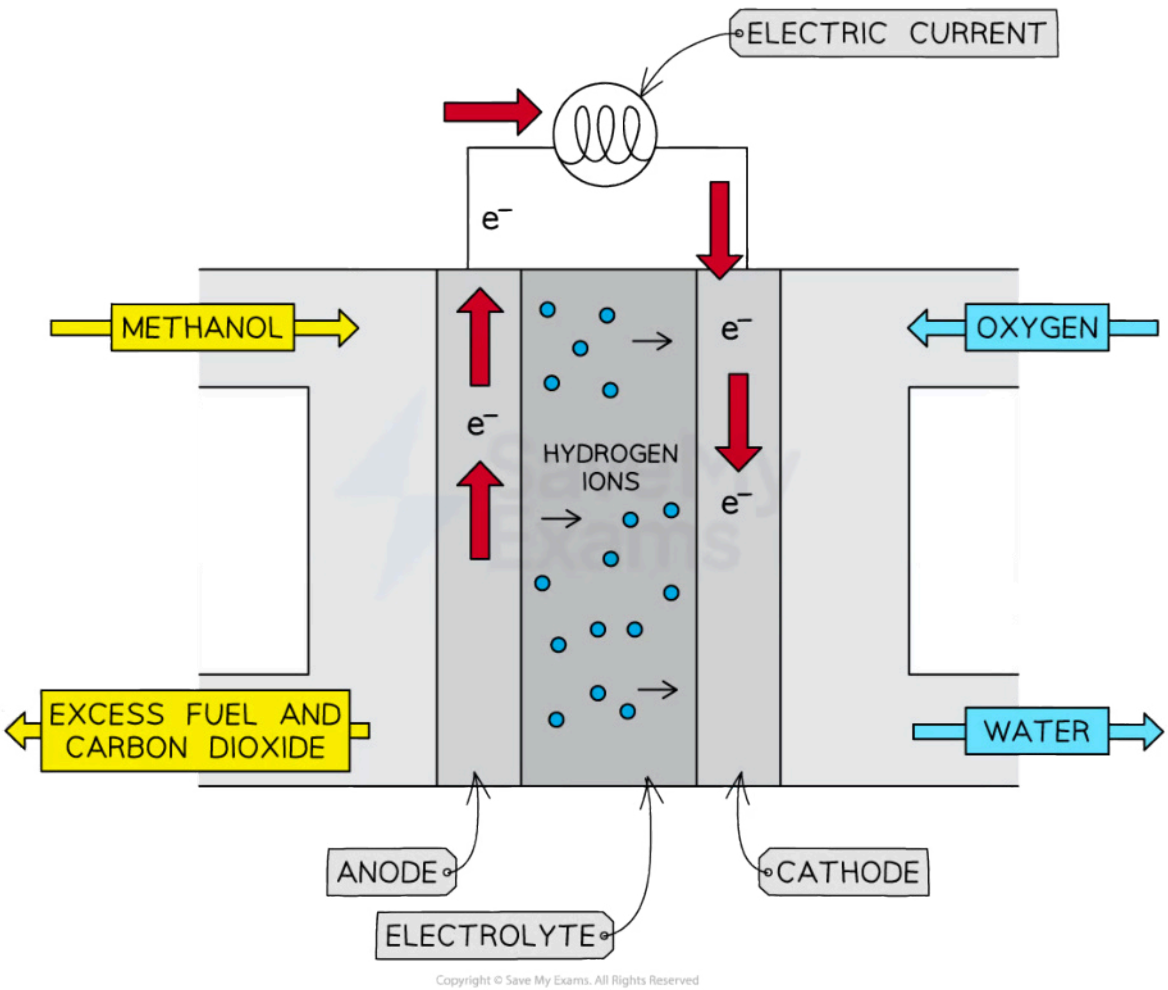
Methanol fuel cell

- The methanol fuel cell works in a similar fashion to the hydrogen fuel cell
- The main difference is that the fuel or source of hydrogen ions, H^+, is methanol rather than hydrogen

The methanol fuel cell

Your notes

Your notes



The methanol fuel cell uses methanol as the course of hydrogen ions and produces carbon dioxide and water while releasing energy

- The methanol fuel cell consists of:
  - a reaction chamber with separate inlets for methanol and oxygen
  - outlets for the carbon dioxide and water products
  - an electrolyte, typically a proton exchange membrane
  - a semi-permeable membrane that separates the hydrogen and oxygen gases
- This use of methanol as the source of hydrogen ions means that the half-equations and overall equation for the cell will be different
- The half equations are:

$$CH_3OH\,(aq) + H_2O\,(l) \rightarrow CO_2\,(g) + 6H^+\,(aq) + 6e^-$$

$$O_2\,(g) + 4H^+\,(aq) + 4e^- \rightarrow 2H_2O\,(l)$$

- The overall reaction is found by:

Your notes

- Multiplying the O_2 equation by 1.5
  $$1.5O_2\,(g) + 6H^+\,(aq) + 6e^- \rightarrow 3H_2O\,(l)$$
- Combining the two half equations
  $$CH_3OH\,(aq) + H_2O\,(l) + 1.5O_2\,(g) + 6H^+\,(aq) + 6e^- \rightarrow CO_2\,(g) + 6H^+\,(aq) + 6e^- + 3H_2O\,(l)$$
- Cancelling the common terms
  $$CH_3OH\,(aq) + 1.5O_2\,(g) \rightarrow CO_2\,(g) + 2H_2O\,(l)$$

Advantages of methanol fuel cells over hydrogen fuel cells

- Methanol is easier to store and transport than hydrogen
- The fuel cell does not require high pressure or temperature
- The membrane has a longer lifespan as it is operating in an aqueous environment
- Methanol has a greater energy density (energy per unit volume) than hydrogen
- Methanol can be produced from renewable resources through fermentation
  - This means that methanol is cleaner than hydrogen because its production has less impact on the environment in terms of greenhouse gases.

Disadvantages of methanol fuel cells over hydrogen fuel cells

- Methanol is very toxic and highly flammable
- Methanol is most commonly made from non-renewable fossil fuels
- The fuel cell produces a lower voltage / lower power per unit mass of the cell
- The fuel cell has a low efficiency because methanol can pass through the available membrane materials
- The reaction at the anode requires a more highly efficient catalyst that contains expensive precious metals, usually ruthenium and palladium
- The fuel cell produces the greenhouse gas, carbon dioxide